FULL SCALE TESTS ON BOLTED CONNECTIONS
Tests on beam-to-beam end-plate connections under bending

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INTRODUCTION

The paper presents the details and results of an experimental study on bolted end-plate joints of industrial type steel building frames. The investigated joints are commonly used by Lindab-ASTRON and these are optimized for manufacturing, erection and durability.

The aim of the research was to provide an experimental background for the design model development by measuring the load bearing capacity of the joints, determining the bolt force distribution, and the end-plate deformations. Because of the special joint arrangement, the Eurocode 3 component model was improved to complete the design resistance calculation. The key special arrangements are: a.) four bolts in a bolt-row, b.) “Hammerhead” type connection plate overhang as presented in *Fig. 1* and *Table 1*.

In the experimental programme 18 full scale specimens were studied, they covered eight different end-plate and bolt arrangements. The bolt qualities were 8.8 and 10.9 with diameter of 20mm. The end-plate thicknesses were between 12mm and 24mm.

The specimens were investigated under pure bending conditions using a four-point-bending arrangement (specimen length 8000mm, beam height 1000mm), in which the test specimens, were changed, as shown in *Fig. 2*.

In all tests the typical displacements were measured by inductive transducers under the loads and in the cross-section of the tested joint. The bolt force distribution was registered by special load cells, developed for this purpose. After the test, the end-plate deformations were measured by an automatic measuring device.

The measured data were presented and evaluated by the following diagrams: moment-bolt-row force diagrams, moment-deflection diagrams and the deformed end-plate surfaces.

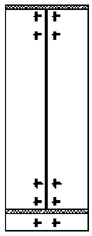
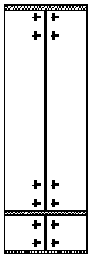
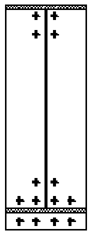
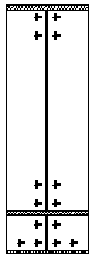
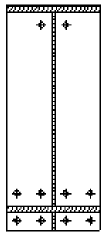
1 RESEARCH PROGRAMME

1.1 Purpose of the study

The purpose of the research was to perform experimental and analytical studies on different bolted, end-plate joint arrangements. The tested joint arrangements are used in portal frames of Lindab-ASTRON industrial buildings, and because of the innovative arrangements, there are uncertainties in their behaviour which are not supported by standardized design rule. The investigated joint types are shown in *Table 1*.

The research concentrated first on the physical phenomena and resulted in practically applicable design information. In the research strategy interacting experimental, analytical and numerical tools were used. This paper has a focus on the experimental part of the research; the whole research study is presented in details in [1].

Table 1. Details of the investigated joints

				
a.) standard joint arrangement	b.) HammerHead joint arrangement	c.) joint with four bolts in one row	d.) HammerHead joint arrangement and joint with four bolts in one row	e.) joint with four bolts in one row and an additional stiffener in the first bolt-row
The joint can be designed, the EC3 component model method can be used, without adjustment.	In the extended tension zone the end-plate has two bolt-rows and an additional flange.	In the end-plate the bolt-rows contain four bolts in the first and second bolt-rows.	The design problems indicated in b.) and c.) are combined in this joint.	The design problem indicated in c.) and an additional stiffener in the first (extended) bolt-row.

1.2 Test specimens

Tables 2 and *3* show a summary of the test specimens with their bolt arrangements, end-plate type and end-plate thickness. *Fig. 1* gives the short explanation of the so called HammerHead arrangement. This is an additional short web and flange, which are located on the tension side of the girder.

Table 2. Test specimens in series I

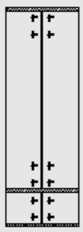
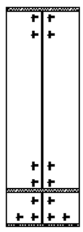
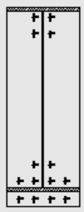
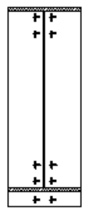
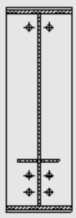
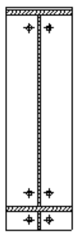
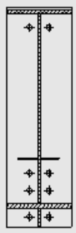
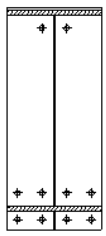
end-plate arrangement												
end-plate type	I			II			III			IV		
test specimen	TB2	TB6	TB10	TB3	TB7	TB11	TB4	TB8	TB12	TB5	TB9	TB13
end-plate thickness t_{ep} [mm]	12	15	20	12	15	20	12	15	20	12	15	20

Table 3. Test specimens in series II

end-plate arrangement						
test specimen	TA	TB	TC	TD	TE	TF
end-plate thickness t_{ep} [mm]	16	20	20	16	20	24

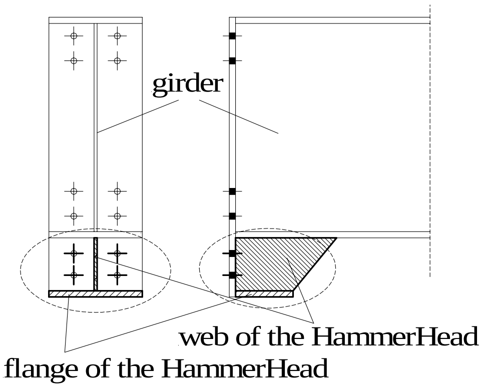


Fig. 1. The HammerHead arrangement

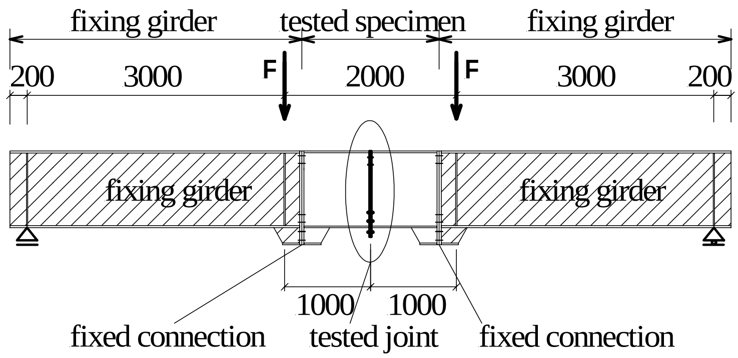


Fig. 2. The test arrangement

1.3 Test arrangement

The specimens were investigated under pure bending conditions, applying a four-point-bending arrangement, in which the test specimens were changed. The specimens were erected between fixed girders, as shown in *Fig. 2*. These supporting beams served the economy of the fabrication of the specimens. The two concentrated loads were applied by hydraulic jacks with capacities of 400 kN. Because of this load configuration, the tested part, including the investigated joint, was loaded under pure bending. To prevent lateral buckling of the beam, both flanges were restrained close to the load introduction point.

1.4 Measuring system

During the tests representative displacements were measured by inductive transducers placed under the loads and in the cross-section of the investigated joint. The distribution of the bolt forces was registered by load cells, developed for this purpose. The measured data were collected at one second intervals, by two HBM Spider data collection systems. *Fig. 3* shows schematically the locations of the transducers and the load cells.

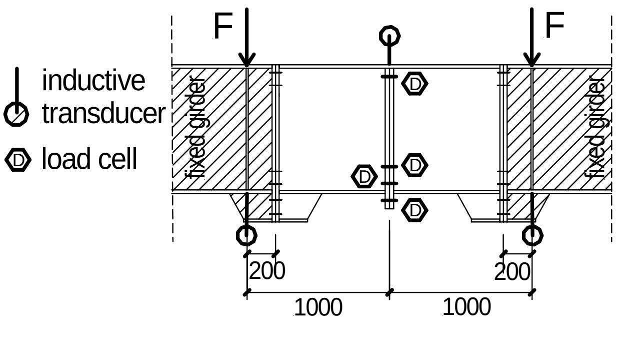


Fig. 3. Locations of transducers and load cells

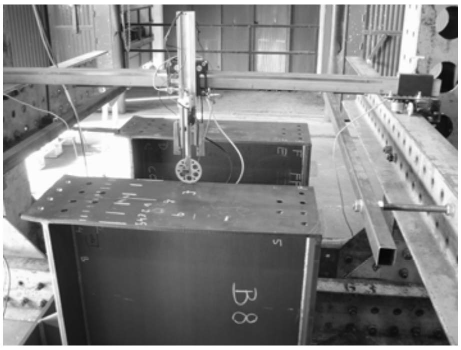


Fig. 4: Measuring the plastic deformation of the end-plate

The purpose of measuring the end-plate deformations in the elastic phase was to analyze the load vs. deformation relationship and to find out how plate deformations develop up until the ultimate limit state. Note that the surface deformation of the end-plates is difficult to measure during the tests; in the previous research this measurement is usually focused only on the edges of the end-plates.

In the completed tests, in the elastic phase of joint behaviour, the end-plate deformations were measured by portable inductive transducer. The measuring points - drilled holes in the plate - were placed so as to give representative points of the expected deformation but at the same time not to

disturb the development of yield lines or the load bearing capacity of the joint. Therefore, on the one hand, an appropriate number of measuring points needed to be defined so as to achieve an adequate accuracy of the deformation values determined, while on the other hand, one needed to be careful not to place too many such points so as not to disturb the yield line pattern to develop. For this reason half of the measuring points were placed in one end plate, and the other half in the other plate, following a pattern symmetrical to the web.
After the test the plastic end-plate deformations were measured by an automatically running and measuring device – as shown in *Fig. 4* – and the benchmark data are collected.

2 TEST RESULTS

The data collected during the tests were prepared and presented by the following diagrams: moment-bolt-row force diagrams, moment-deflection diagrams and furthermore figures of the deformed end-plate surfaces. The following illustrates the results for a typical joint.
Fig. 5 illustrates the selected test specimen TB3 before the test and the deformed tension zone after the test, respectively. The observed ultimate behaviour of the joint was dominant plate failure.

a.) b.)

Fig. 5. Specimen TB3 - arrangement and failure mode

The moment vs. bolt-row force diagrams show the relationship of the measured force in the bolt-rows and the moment in the tested joint. *Fig. 6* illustrates, as an example, the moment and bolt-row force relationships of test TB3.

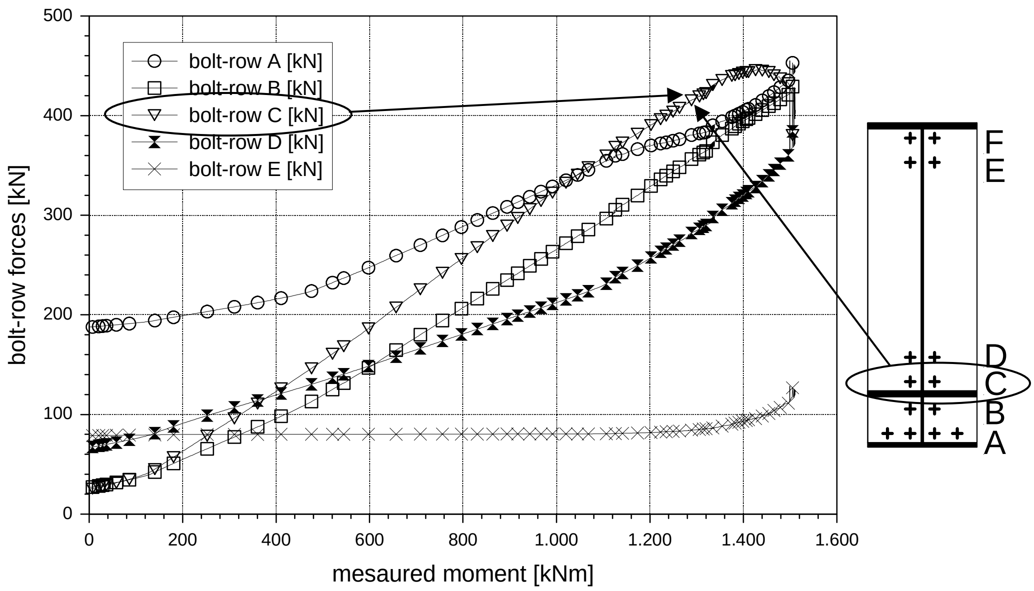


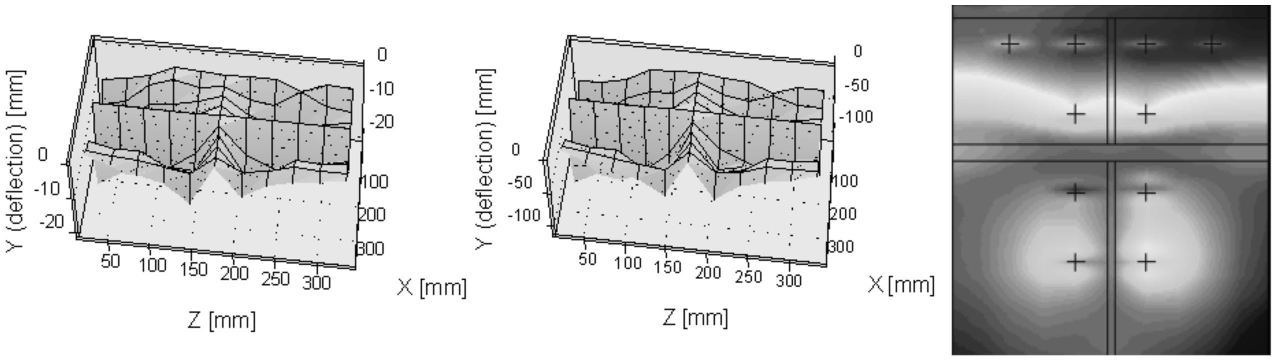
Fig. 6. Moment vs. bolt-row force diagrams of specimen TB3

Because of previous load steps and different pre-tensioning levels of the bolts, the presented bolt-force curves have different starting points. For reasons of clarity, in each diagram of the measured bolt forces presents the force for the whole bolt-row.

The moment vs. bolt-row force diagrams show how the force increment changes in the bolt-rows and in which part of the joint i.e. which bolt-row accumulates higher forces. The diagrams show in the given case of specimen TB3, that the highest force increment was obtained in bolt-row C, below the members tension flange. This phenomenon was explained by the non-homogenous stiffness distribution of the end-plate.

The end-plate deformations of specimen TB3 in the elastic phase are shown in *Figs. 7 a.)* and *b.),* while the plastic deformations can be seen in *Fig. 7 c.).*

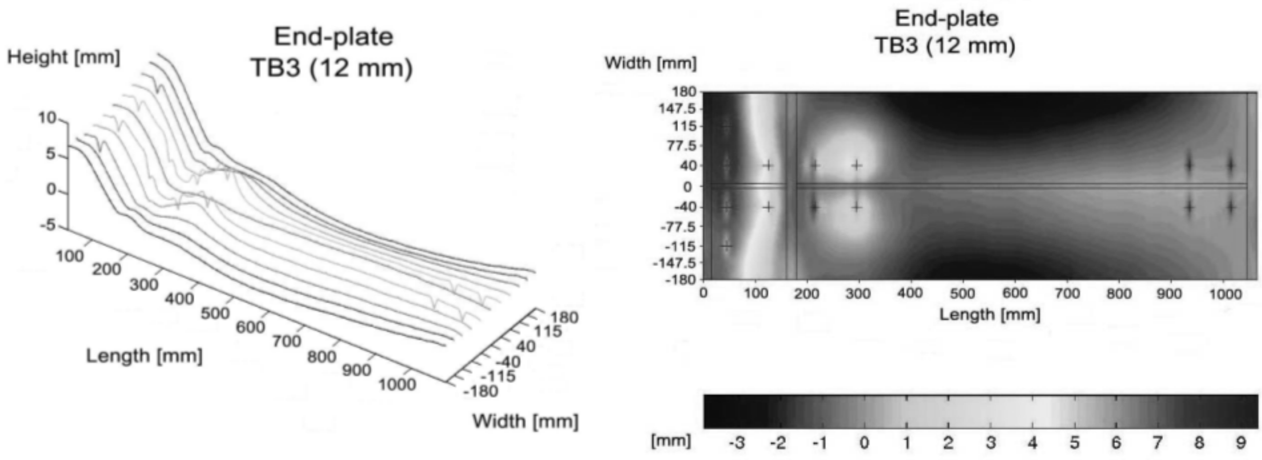
Eurocode 3 gives design methods to determine the end-plate deformations, i.e. the yield line pattern, in the ultimate limit state, but it does not inform about the load-deformations equilibrium in the phases when the behaviour is still elastic. This study aims at identifying the “path” that leads from elastic to plastic deformations and finding the relationships among these deformations.



a.) elastic phase (552 kNm) b.) elastic phase (1,050 kNm) c.) plastic phase (1,511 kNm)

Fig. 7. The end-plate deformations in the elastic and the plastic phases of the specimen TB3

Fig. 8 shows the results of the measurements of the deformed end-plate of specimen TB3 after the test and presents the deformations by contour-lines and from the contour-lines is derived the deformed surface of the end-plate which was calculated by linear interpolation between the contour-lines.



a.) deformed end-plate contour-lines b.) the shape of the deformed end-plate

Fig. 8. Evaluated results of the measurement on the deformed end-plate of specimen TB3

From the measuring results, in the elastic phase, it is concluded that the 3D deformation diagrams show similar failure modes as those corresponding to the ultimate failure already at relatively low load levels that correspond to the elastic phase of joint behaviour. This shows that the governing end-plate deformations can already be identified in the phase of elastic behaviour. This observation, together with the measuring method developed could be useful for forecasting failure modes.
In *Fig. 8* it can be seen that the end-plate also deforms within the level of the flange of the HammerHead arrangement, these deformations were mirrored in the moment vs. bolt-row force diagrams (*Fig. 6*). And this deformation was the reason that the highest bolt-row force was measured in bolt-row C, followed by bolt-row B.

3 CONCLUDING REMARKS

Based on the experimental results of the study, for practical applications the following design rules can be derived:

- In relation to the HammerHead joint design, it is pointed out that, as far as possible, the bolts should be placed close to the "stiffened joint elements", i.e. the tension flange.
- On the basis of the results obtained, it has been shown that the four bolts in one row joint arrangement is a competitive solution from the point of view of load capacity when compared to solutions such as the redesign of the bolt arrangement or increasing the overall dimensions of the beam. On the basis of the experimental results it is suggested to place the bolts symmetrical to the tension flange so as to achieve the most favourable utilization ratio in the bolts.
- On the basis of the experimental results was pointed out that triangular stiffeners are efficient and can to enhance the tension resistance of the web and to avoid bolt group failure.

More details on the tests can be found in [3] and [4]; the developed design method is detailed in [1].

4 ACKNOWLEDGEMENT

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